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STUDY OF EXPERIMENTAL TECHNIQUE OF OIL FLOW WITH EMPHASIS ON QUANTITATIVE DETERMINATION OF THE FLOW POSITION PARAMETERS ON THE SURFACE

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STUDY OF EXPERIMENTAL TECHNIQUE OF OIL FLOW WITH EMPHASIS ON QUANTITATIVE DETERMINATION OF THE FLOW POSITION PARAMETERS ON THE SURFACE

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Abstract

This paper discusses the reliability of the flow pattern obtained with the surface oil flow technique in detail. It successfully introduces a mathematical method to determine the three-dimensional coordinates of a surface point based on a single photograph. The flow separation positions of the classical plate and blunt cone model were calculated. The results indicate that in most cases the surface oil flow technique can be applied not only as a qualitative but also a quantitative experimental technique.

1. Introduction

The surface oil flow technique is a way to study aerodynamic flow along the surface of an object. It is visual, direct, rapid, simple and economical. In addition to being used in the study of boundary layer transition, it is frequently used to determine surface flow parameters such as the locations of boundary layer separation and re-attachment, and the position of shock wave - boundary layer interference. In certain circumstances, there is no other interference free method to conduct the study. The oil flow technique can easily accomplish the job, such as in the study of three-dimensional flow in the turning corner. The data is crucial to the design and modeling work. Therefore, everyone

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in aerodynamics pays attention to this technique. However, the research and application of oil flow technique still remains at a primitive level. At best, it provides some reference data. There are two reasons. One reason is that due to the presence of the oil layer, the original flow must be interfered with which easily makes people doubt about the truthfulness of the flow pattern it displays. In the early 1960's, L. C. Square theoretically proved that this technique could not accurately display the flow near the separation line[1]. To date, many people still believe that it is a qualitative technique. This will affect the reputation and development of the oil flow technique. The other is that analytical photography was not fully developed in the prime days of oil flow technique. Even now, few people in aerodynamics study it in depth. Despite the fact that people hope to obtain important parameters such as separation position quantitatively from the flow pattern picture, we have not yet seen any article in this area. Over the years, we used the oil flow technique to systematically conduct studies in the FL-31 hypersonic wind tunnel. The Mach number ranges from 4.95 - 11.73 and the free flow Re number from 4.7×10^7 - 5.08×10^9 1/m. A relatively complete set of experimental technique has been developed to obtain a fine and accurate separation line. It was experimentally discovered that the thickness of the oil film has no significant effect on the separation position. The accuracy of the statement that the surface oil flow technique is only a qualitative tool needs to be discussed. (1) How much interference is there due to the presence of the oil layer? Or, what are the conditions under which this interference is tolerable?

(2) Can or how would an aerodynamic researcher accurately provide parameters such as positions for separation and re-attachment, and the location of the shock wave and boundary layer interference region based on a photograph of the flow pattern?

2. Reliability of Surface Oil Flow Pattern

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Based on the study and order of magnitude analysis done by L. C. Squire on the thin oil layer induced motion below the boundary layer, we can deduce that this method has some accuracy [1].

1) Assumptions

When y = h,

$$u_{oil}=u_{air};$$

$$\mu_{oil}\cdot\frac{\partial u_{oil}}{\partial y}=\mu_{air}\cdot\frac{\partial u_{air}}{\partial y};$$

When y = 0,

$$u_{oil}=0;$$

$$p_{oil}=p_{air}=p(x),$$

$$\frac{\partial u_{oil}}{\partial t}+\frac{1}{\rho_{oil}}\cdot\frac{\partial p}{\partial x}=\frac{\mu_{oil}}{\rho_{oil}}\left(\frac{\partial^2 u_{oil}}{\partial x^2}+\frac{\partial^2 u_{oil}}{\partial y^2}\right)$$

We get

$$u_{oil,h}=\frac{\mu_{air}}{\mu_{oil}}\left[-\frac{h^2}{2}\left(\frac{1}{\mu_{oil}}\cdot\frac{\partial p}{\partial x}\right)+h\left(\frac{\partial u_{air}}{\partial y}\right)_h\right]$$

This equation is obtained under the assumptions that the boundary layer thickness and the air to oil viscosity ratio are small and the boundary layer thickness and oil layer thickness are of the same order of magnitude. As long as $u_{oil,h}$ is very small, $u_h/u_\infty < 1\%$, the oil layer can stabilize the flow.

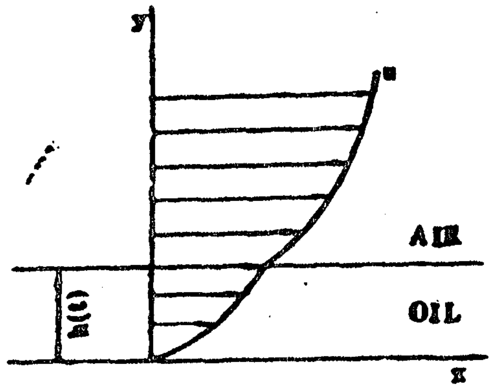

Figure 1 Schematic Diagram of Oil Layer Induced Motion

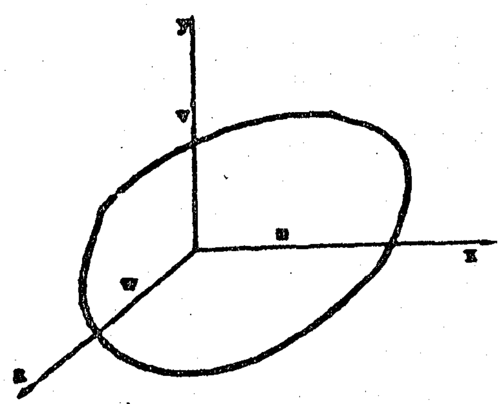

Figure 2 Schematic Diagram of Point Mass Velocity

2) Direction of Stream Line in Oil Layer

When there is no oil, the direction of flow of a point mass along the wall is

$$\frac{dx}{dz}=\left(\frac{u_{air}}{w_{air}}\right)_{y\to 0}=\frac{(\partial u_{air}/\partial y)_{y=0}}{(\partial w_{air}/\partial y)_{y=0}} \quad (2)$$

The direction of the steam line in the oil layer can be approximately expressed as

$$\frac{dx}{dz} = \frac{(\partial u_{air}/\partial y)_{y=0} \cdot \mu_{air} + \frac{\partial p}{\partial x}\left(\frac{y}{2} - h\right)}{(\partial w_{air}/\partial y)_{y=0} \cdot \mu_{air} + \frac{\partial p}{\partial z}\left(\frac{y}{2} - h\right)}$$ /385

Here, the author assumed that $\tau_{air,y=0} \approx \tau_{oil,h}$

3. Discussion on the Equation

It is generally believed that the largest negative impact due to the presence of the oil layer is from the term $\partial p/\partial x$, especially near the position of separation. $\partial p/\partial x$ may be so large that $u_{oil,h}$ is also very large. There is severe deviation of the direction of the stream line. Therefore, surface oil flow cannot accurately (quantitatively) display the position of separation. Therefore, it is only a qualitative tool. Relatively speaking, far away from the separation line, $\partial p/\partial x$ is small and would not be a problem. (Even in some areas such as the leading edge of the airfoil, $\partial p/\partial x$ may be large, this technique would not be used.) The following discussion is focussed on the situation near the separation line.

How large is $\partial p/\partial x$? We did a rough statistical analysis on the pressure measurement results and found that, except for low Mach number wing experiments at subsonic and transonic speeds, in most cases the pressure gradient in the separation area is in the range of 9.8×10^2 - 9.8×10^4 Pascal/m (10^2 - 10^4 kg/m^2.m). If the viscosity of oil is 10 cp and the oil layer thickness is 0.1 mm, $u_{oil,h}$ should be in the range of 10^{-3} - 10^{-5} m/sec. This is of course permitted. As for equation (3), the last term of the numerator is one to two orders of magnitude lower than the first term of the denominator. It must be pointed out that 0.1 mm is very thick for an oil layer. If we carefully choose the flow medium and the formulation, it will not be difficult to lower it further by one to two orders of magnitude. The stream line direction near the separation position would not be interfered significantly. Hence, the stream line and separation position shown by the oil flow pattern are accurate and dependable in most

cases. However, in transonic and some low Mach number supersonic airfoil tests, the pressure gradient may reach 10^5 and even up to 10^9 $kg/m^2.m$. Nevertheless, this would not affect $u_{oil,h}$ much. However, as far as the direction of the stream line is concerned, it is still valid if $\partial p/\partial x \in 10^5$ and $h \in 10^{-3}$. If $\partial p/\partial x$ is of the order of 10^6, the stream line direction near the separation position will be changed. We must be aware of it when we perform this type of experiments. However, we also found that in these experiments strong pressure change was limited in a range of within 0.05 chord length. The most was less then 0.1 chord length. It is believable that the distance between the leading edge to the separation position would not be changed by more than 2% due to the presence of oil film when the oil flow technique is used in the flow around the wing. In reality, this kind of accuracy is also valuable.

In summary, the flow pattern provided by the surface oil flow technique is accurate and reliable in most situations. It can be safely used as a quantitative tool. Even in the worst case, it can provide very useful results. Therefore, we should not jump into the conclusion that it is merely a qualitative tool to undermine its reputation and capability. In most cases, it is a quantitative technique. As long as we know what we are doing, it is an accurate and reliable experimental tool with many unique features. In reality, there are few quantitative experimental techniques in flow display that do not have any limitations.

3. Data Processing of Flow Pattern Photograph

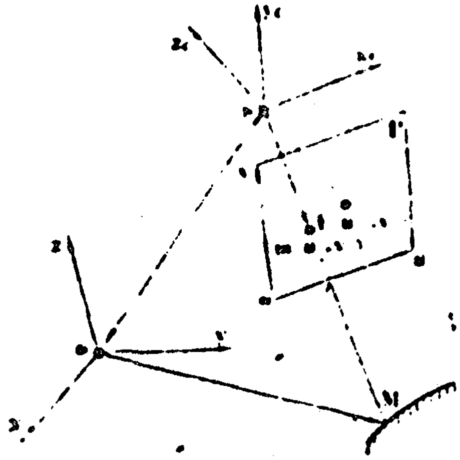

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Figure 3 Coordinate Transformation in Analytical Photography

In processing the data from the flow pattern, we employed the basic theory in analytical photography. To make it brief and concise, only the basic method and the primary part of our work and our views are described.

1) General Data Processing Method[12-15]

Assume that photograph P is taken from point S. The image of a surface point M is m. O_{xyz} is the object coordinate system and o_s is the photograph coordinate system. (u,v) is the primary image point. Let us introduce an auxiliary coordinate system, i.e. the camera coordinate system S_{XcYcZc} and its original is at S. Xc and Yc are parallel to u and v, respectively. Zc coincides with the line of primary light SF. It is obvious that in the S_{XcYcZc} coordinate system the coordinate for image point m is (u, v, -f), where f is the primary focus of the photograph P. The following colinear equations can be derived by using the vector expression.

$$\left.\begin{aligned} u-u_0 &= -f\cdot\frac{a_{11}(x-x_s)+a_{12}(y-y_s)+a_{13}(z-z_s)}{a_{31}(x-x_s)+a_{32}(y-y_s)+a_{33}(z-z_s)} \\ v-v_0 &= -f\cdot\frac{a_{21}(x-x_s)+a_{22}(y-y_s)+a_{23}(z-z_s)}{a_{31}(x-x_s)+a_{32}(y-y_s)+a_{33}(z-z_s)} \end{aligned}\right\} \qquad (3.1)$$

where x_s, y_s, z_s are the coordinates of point S in the object coordinate system and (a_{ij}) is the directional cosine. Based on the above equations, the following parameters are required in order to process the photograph.

(1) x_s, y_s, z_s and (a_{ij}), i, j= 1, 2, 3; these are the external

orientation elements of the camera.

(2) u_o, v_o and f; these are internal orientation elements of the camera.

They impose rigorous requirements for the camera, photograph reader and experimental environment and conditions. Based on specific situations in a wind tunnel experiment, it is inconvenient to use these equations directly. It is easy to make an error. If they are not explicit functions, these elements can avoid such problems. The above equations can be transformed into

$$\left.\begin{aligned} u+\frac{L_{11}X+L_{12}Y+L_{13}Z+L_{14}}{L_{31}X+L_{32}Y+L_{33}Z+1}=0 \\ v+\frac{L_{21}X+L_{22}Y+L_{23}Z+L_{24}}{L_{31}X+L_{32}Y+L_{33}Z+1}=0 \end{aligned}\right\} \qquad (3.2)$$

There are three main advantages in using these equations to process the photograph.

(1) It only takes 6 control points to determine the relation between the photograph coordinate system and the object coordinate system.

(2) Since the origin of the photograph coordinate system can be arbitrarily chosen, the processing work is simplified and performance specifications of various instruments are also lowered.

(3) Because what we have established is an instantaneous relation between the object and the image, the accuracy of the data would not be affected by the stability of the site and the noise movement of the camera itself. The picture can be shot with hand-held or fixed camera. /387

2) Feasibility of the Determination of Three-Dimensional Coordinates of a Solid Object by Evaluating a Single Photograph

From equations (3.1) and (3.2) we found that each photograph can provide two equations. The conventional way to treat a three-dimensional problem in analytical photography is to use a pair of solid pictures or several pictures. This is convenient to do in most cases. However, in many wind tunnel experiments such as oil

flow tests, the most interesting part we are looking for may be a curve or surface. It involves many random points and there is no way to provide any recognizable characteristics. We believe that regardless of the method, if the target point (x, y, z) can be correlated to supplement the equations, then it will be possible to treat a three-dimensional problem with a single photograph. For example, if the equation of the object surface is

$$F(x, y, z) = 0 \qquad (3.3)$$

Make it simultaneously valid with the original equations. Then, based on m(u,v) from the picture it is possible to find the value of M(x,y,z) on the surface. F(x, y, z) may be the analytical expression of the surface or may be in the form of discrete points. In general, it is not difficult to establish this relation based on a model.

There are several distinct advantages to determining the target coordinates with a single photograph. First, several points may be conveniently determined which is particularly important in defining a curve or a surface in space. Furthermore, because the problem is solved with a single picture, not only accuracy but also efficiency can be improved. On the other hand, it may not be as easy to use a pair of photographs because it is difficult to find many corresponding points on two pictures. It is even somewhat impossible in some wind tunnel experiments. It is not only time consuming to locate corresponding points but also easy to make mistakes. Therefore, both accuracy and efficiency would be affected.

3) Results

As an example, we wrote a program to process the data with this method. The flow pattern photographs of a blunt cone and a plate were processed by a computer. These photographs were taken with a Japanese Model XD-7 high performance hand-held cameras. They

were read on a universal microscope and calculated on a computer. In order to verify the accuracy of this method, each picture has several check points. The results were compared with the precise coordinates of these points. It was found that the mean square root error of x, y, z was 0.37 mm and the angle error ψ was 0.48° for the blunt cone. The root mean square error of x, y was 0.48 mm for the plate. These results were obtained from photographs that covered a wide area, which are fairly representative. It should be considered quite satisfactory.

separation line   slanted platform   bottom

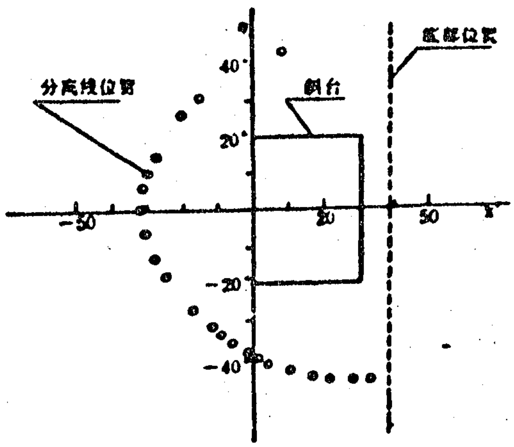


Figure 4 Separation Position for a Blunt Cone + Slanted Platform at a = 0°; experimental conditions: M = 4.95, Re = 2.1×10^{7} 1/m

The data processing scheme described above indicates that the use of a single photograph to determine three-dimensional coordinates is successful and accurate. Since it processes a single picture, we do not have to consider to match corresponding points on different pictures. Therefore, it is more efficient and there is no limit on the number of points. Overall, the accuracy is higher.

plate boundary

separation position

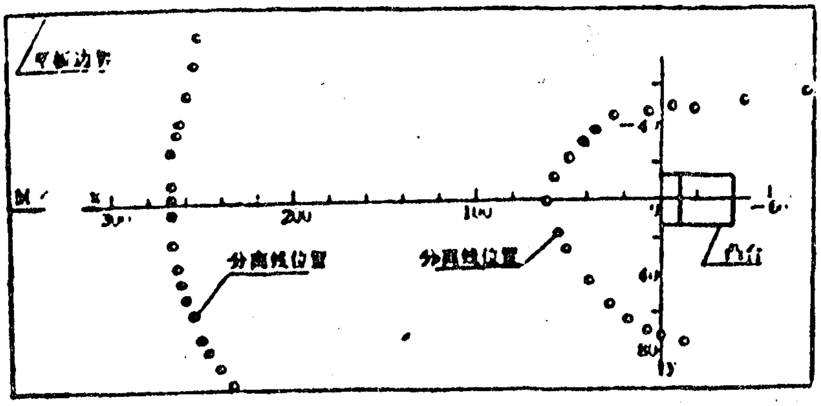
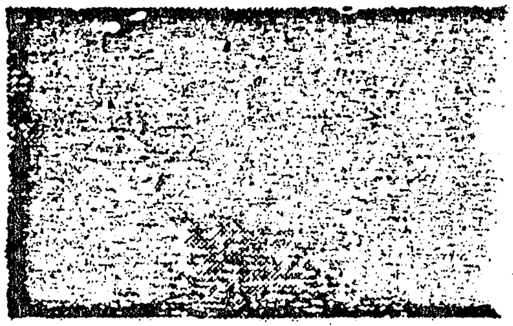


Figure 5 Separation Positions of Plate + Bulged Platform Model

Photograph 1 Flow Pattern of the Blunt Cone + Slanted Platform Model, $a = 0^{\circ}$, $M = 4.95$, $Re = 2.1 \times 10^{7}$ 1/m



Photograph 2 Flow Pattern of the Plate + Bulged Platform Model, $M = 11.71$, $Re = 5.08 \times 10^{6}$ 1/m

4. Conclusions

1) An analysis of the experimental results shows that the surface oil flow technique is a reliable tool in most cases if the layer is very thin. The flow parameters displayed are accurate and dependable (especially in engineering). It may be used as a quantitative experimental technique, instead of a qualitative tool. The application of this unique tool should not be limited by the thought that it is a primitive technique.

2) Important position parameters such as separation, re-attachment, shock wave - boundary layer interference region can be accurately obtained based on the analysis of a photograph. Our results indicate that this non-pair method is more efficient and accurate.

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16. Abstract

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